A SERVICE-ORIENTED APPROACH INTEGRATING INSAR BASED INFORMATION TO ASSESS THE UNSEEN RISKS OF NATURAL AND HUMAN INDUCED GROUND MOVEMENTS AFFECTING URBAN AREAS AND CRITICAL INFRASTRUCTURE

Arnd Berns[1], Robert Siegmund[2], Paul Kotzerke[3], Jürgen Langenwalter[4]
[1]Service-on-Demand Senior Expert, GAF AG,
[2]SAR Processing Development, GAF AG
[3]Head of SAR Data Production GAF AG
[4]SAR Senior Expert, GAF AG
Arnulfstraße 199, 80634 Munich, Germany
Email: arnd.berns@gaf.de

KEY WORDS: PS InSAR, Ground Motion Service, Critical Infrastructure

ABSTRACT: Ground motion and deformation are phenomena that occur globally on both large and small scales. In general, they can be classified into naturally-induced and human-based ground movements. Land subsidence can be related to both seismic/tectonic activities or natural flooding and ground water fluctuations, as well as man-made drivers like socio-economic development factors (urbanisation and population growth), including high-rise and heavy building complexes and increasing amounts of ground water extraction. Due to climate change effects like accelerated sea level rise and extreme weather events, the potential impacts of surface subsidence are being amplified significantly.

For many years, InSAR analysis techniques have been identified and recognised as a mature and reliable remote sensing method offering coverage of large areas and the measurement of movements in the range of millimetres. In recent years, research and development in the Earth observation component of the European Union’s Copernicus Space Programme has addressed SAR technologies and applications, thereby providing continuous progress and achievement that has resulted in operational services based on peer-reviewed feasibility and scientific robustness. The intention of this paper is to present examples of the potential of an operational InSAR Persistent Scatterer (PS) approach, thereby encouraging and promoting the added value for potential down-stream application for detecting silent risks of imperceptible ground motion in urban regions.

1. INTRODUCTION

1.1 Background and Motivation

Global sea level rise is an essential indicator of the changing climate that has been scientifically studied, measured, well-monitored and documented (European Commission, 2023; IPCC, 2023). Observed globally, the sea is edging forwards along shores and coastlines, threatening expanding low-lying metropolitan regions and mega cities. In addition to that, the climate change induced effect is exacerbated by anthropogenic activities resulting in consolidated and slumped underground layers. This effect occurs both locally, varying within an urban area, and also across large plain regions and coastal deltas. Major human-induced processes resulting in underground sinking include excessive extraction of groundwater for domestic and industrial uses, compaction of alluvial soils and aquifers due to the weight of heavy building structures and traffic, and underground infrastructure constructions (Kandarr, 2018).

Wu et al. 2022 measured the subsidence rate of 99 globally distributed coastal cities using the PS InSAR method. The study revealed that the investigated cities with the highest subsidence velocity (mm/yr) are located in South, Southeast, and East Asia. One of the most prominent consequences with which populations there are now confronted more frequently is the risk of flooding. This is becoming larger in extent and longer in time, and the floods are also deeper (Erkens et al. 2015), as a result of torrential rainfall, longer-lasting rainfall, and/or greater encroachment of sea water. Even more importantly, subsiding land both on the local scale and the large scale imposes long-term risks and danger to critical infrastructure sectors, e.g. water management (critical water retention and control services, water supply and wastewater systems), the transportation systems sector, communications sector and energy sector, amongst others. This applies at the national and international levels (CISA, 2023; BSI, 2023).

Persistent Scatterer Interferometry (PSI) using Earth observation satellites is able to acquire data for large areas in a few seconds. The availability of several acquisitions in a time series covering the same area provides the advantage of being able to detect, identify and measure wide-area ground surface movements in the range of millimetres and deformation of the structure of individual buildings and infrastructure facilities. In a comparison with typical geodetic measuring methods like optical levelling and GPS survey, the PSI measurements are spatially sampled at the positions of measurement points and distributed in relation to existing stable reflecting objects. Their density depends on the number of reflectors, so a large number of measurement points is available in urban areas.

The motivation for this paper is to demonstrate further impressive examples of using the well-established PSI technology to uncover and visualise silent risks in time. This information can be used to support decision making and the coordination of relevant and proper countermeasures against long-term ground subsidence phenomena. A positive and promising example is the megacity of Tokyo (see Figure 1), which stands out as an example of how subsidence can be successfully stopped as a result of the implementation of proper mitigation measures (Cao et al. 2021).

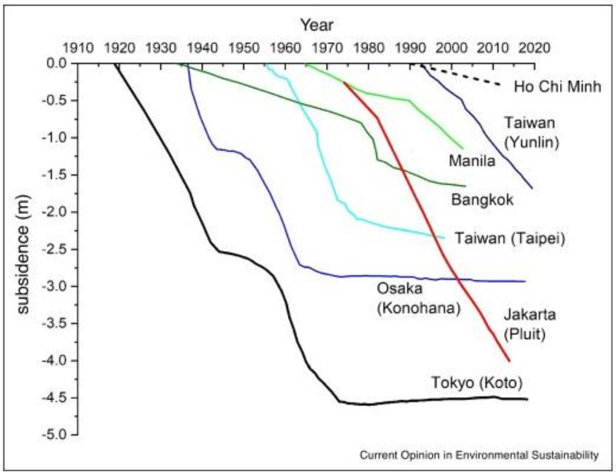

Figure 1 Cumulative maximum land subsidence in major cities in the Asia-Pacific Region (Cao et al. 2021)

1.2 References

Over the last few decades, the availability of SAR data has increased both in terms of commercial distributed data and data sets from former SAR missions made available for free. A significant boost of free accessible SAR data has occurred as a result of the two Sentinel-1 satellites (1-A and 1-B) of the Copernicus Programme conducted by the European Space Agency. This development has been leveraged by several initiatives at the national level to harness the vast data sets, and to make use of enhanced data processing and analysis techniques. For example, Italy has introduced and maintains region-wide InSAR monitoring services, and Norway and Germany have implemented nationwide ground motion services based on Sentinel-1 data (Cosetto et al. 2020). In parallel, increasing and highly-performant Big Data processing capabilities and computational capacities are enabling the implementation and continuation of the European Ground Motion Services (EGMS).

GAF AG, as an implementing entity for international and national operational projects, created and provided the German Ground Motion Service (BBD) implemented by the German Federal Institute for Geosciences and Natural Resources (BGR). GAF AG is also a partner of the international project consortium for the European Ground Motion Service (EGMS). Both of these are performed in strong cooperation with the Remote Sensing Technology Institute (IMF) of the German Aerospace Center (DLR), with the service being provided to the European Environment Agency (EEA). As part of the Copernicus Emergency Management Service Risk & Recovery Mapping Service, GAF AG also offers ground motions analysis and map products.

These base services were recently implemented in order to ensure the availability of large scale and wide area base surface deformation products with high precision and quality. With the availability of the infrastructure and optimised PSI technology that is operated at large scales and data volumes, all the products have been assessed by the relevant authorities and are currently validated in real world scenarios by the user communities. Research and development are currently ongoing, addressing the valorisation of representative interferometric products for critical infrastructure monitoring, risk management and sustainable development.

2. OPERATIONAL SERVICE ENVIRONMENT

2.1 Methodology

The Persistent Scatterer InSAR (PSI) is a time-series analysis technique that processes a certain number of input images to provide a time series of measurements. Time series data is useful and an advantage in revealing long-term deformation rates and deviations from the average velocity, e.g. accelerations, and assists in understanding motion trends and evolution. The concept of PSI is based on the long-term presence of single or dominant scatterers (Figure 2). Accordingly, the PS-InSAR technique refers to objects in the area of the image that produce a constant and characteristic radar reflection over time. Such ‘persistent scatterers’ are points that are tracked over time in a stack of many SAR images.

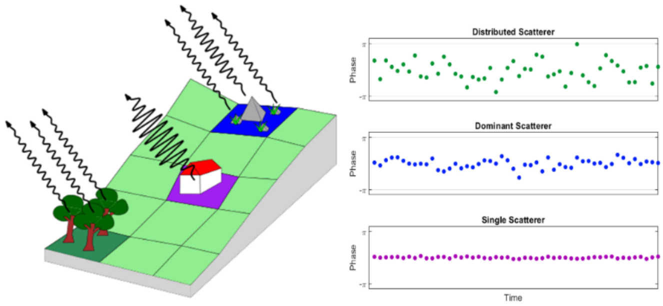

Figure 2 Types of scatterer within one resolution cell (Universität Stuttgart, 2023)

Due to the characteristics of the PSI approach, there are limitations to be considered:

- only deformation in the Line-of-Sight direction of the SAR sensor; no measurement is possible in the north-south component
- sudden changes of the ground or surfaces are measured ambiguously
- in large contiguous areas of dense vegetation, there are few stable reference points
- an extreme topography orientation perpendicular to the Line-of-Sight does not allow the capturing of measurement points
- observations of water bodies or periodically flooded coastal areas are not possible

The approach, and associated algorithms, applied to obtain the results presented within this paper is called the Integrated Wide Area Processor (IWAP). The methodology and algorithms have been developed by the Remote Sensing Technology Institute (IMF) of the German Aerospace Center (DLR) and have been licenced by GAF AG for operational applications and services in the PS-InSAR domain. The functionality of IWAP complies with standards and meets performance requirements, especially with regard to hybrid evaluation, motion decomposition, scalability and customisability. For more information and a detailed description of the algorithms, please refer to the respective documents (Rodriguez et al. 2013) and guidelines of the EGMS (EEA, 2023a). Standard quality control procedures following implemented protocols ensure the fulfilment of the requirements for workflow steps, intermediate data and final output products (EEA 2023b).

Currently, all the algorithms and applied methodologies are also being continuously improved and optimised, and innovative scientific developments are evaluated and implemented in the operational processor. All developments, including software development and processing workflows, are quality assured and the products are quality controlled in accordance with ISO standards.

2.2 SAR time-series input data

The examples presented in this paper have been generated as part of already completed, or still ongoing projects based on data from the Sentinel-1constellation, and databases for the European Ground Motion Service (EGMS) and German Ground Motion Service (BBD). Data from the higher resolution imagery from the twin TerraSAR-X and TanDEM-X constellation, complemented by the almost identically designed Spanish PAZ satellite, provides a higher information density of measurement points (see Figure 5) for use cases relating to critical infrastructure deformations.

- Sentinel-1 data availability

The Sentinel-1 constellation of the Copernicus Programme was originally composed of two satellites, Sentinel-1A (launched 3 April 2014) and Sentinel 1-B (launched 25 April 2016), which were designed to improve the capabilities and capacities of the precursor missions ERS-1/2 and ENVISAT in terms of reliability, revisit time, geographical coverage and rapid data dissemination. Unfortunately, by the end of 2021 Sentinel-1B encountered anomalies in data transmission, and since then no Sentinel-1B data has been acquired to complement Sentinel-1A. Despite the loss of Sentinel-1B, the mission has provided unprecedentedly consistent and reliable data time series. Basically, the minimum input data availability for PSI analysis using C-band SAR imagery requires at least 15 -20 scenes (Crosetto et al. 2015).

The examples that contain Sentinel-1A and -1B data are time series covering all the relevant acquisition years since launch and until the unexpected end-of-lifetime of Sentinel-1B. As part of the European Copernicus Earth Observation Programme, all Sentinel-1 data is free of charge and accessible on various data hubs, as long as the associated general terms and conditions are acknowledged.

Table 1 Sentinel-1 specifications (selective)

Sentinel-1 C-Band	Launch	Acquisition modes (selective)	Interferometric wide swath	Repetition rate
1A	03.04.2014	IW mode (20 m x 5 m)	250 km	6 days (including 1B) – 12 days
1B	25.04.2016 – 23.12.2021	IW mode (20 m x 5 m)		

- TerraSAR-X/TandemX/PAZ data availability

Unlike the freely available Sentinel data sets, the X-Band SAR sensors provide commercial data that is subject to end-user licence agreements, except for scientific research and application development. ESA offers limited access to archive and new tasking data.

Table 2 X-band constellation specifications (non-exhaustive)

X-Band SAR satellites	Launch	Relevant acquisition modes (selective)	Coverage (selective)	Repetition rate
TerraSAR-X	15.06.2007	Spotlight (1 m), StripMap (3 m),	5 x10 km 10 x 10km 1500 x 30 km	11 days
TandemX	21.06.2010	Spotlight (1 m), StripMap (3 m),		
PAZ	22.02.2018	Spotlight (2 m), StripMap (3 m),	10 x 10km 30 x 50 km	
COSMO-SkyMed 1 – 4 Constellation	08.06.2007 - 06.11.2010	Spotlight (1 m) Himage (3 m),	10 km swath 40 km swath	1 – 8 days

2.3 Computational resources and infrastructure

The Integrated Wide Area Processor (IWAP) was specially developed for use in a scalable environment with configurations of computer clusters. All computing processes are optimised for this IT architecture, resulting in high throughput with high reliability, stability and degree of automation. According to reference projects, e.g. BBD and EGMS, InSAR data stacks of the Sentinel-1 with stack sizes of approx. 300 images (temporal extent 2015-2020 & spatial extent of 250 km x 200 km) can be processed to create the final products in a few days.

Table 3 Dedicated Cloud computing specifications at GAF

Flavour	Quantity	vCPU	RAM	Storage memory
Dedicated Host	26	48	512 GB	14-37 TB EVS-SATA
OBS Standard	4	-	-	128 TB
OBS Warm	1	-	-	> 3500 TB

2.4 Information extraction

By default, the information that is generated by the IWAP processing workflows can be provided with three different consecutive standard product levels. In principle, this concept follows the product description of the EGMS ground motion products. In terms of products, the output data is delivered in the form of standard data products following existing conventions:

Level 2: Line-of-sight (LOS) products consisting of mean velocities and time series of deformation per image stack.

- L2a - uncalibrated
- L2b - GNSS calibrated/mosaicked

Level 3: Motion decomposed products, L3 product (Ortho), consisting of mean velocities and time series decomposed into

- vertical/altitude and
- east-west direction

Figure 3 lists the major characteristics for each product. Figure 4 graphically compares the product types.

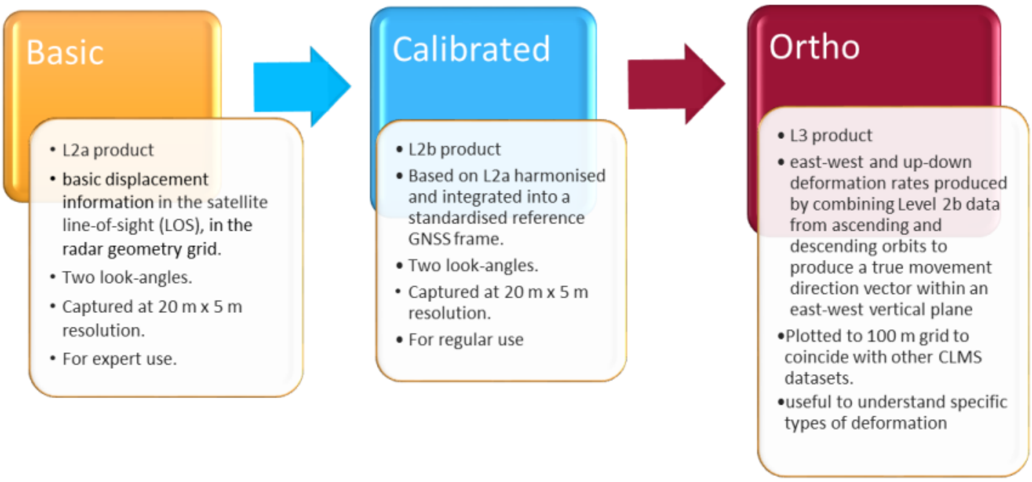

Figure 3 Standard products workflow of the EGMS (EEA, 2022)

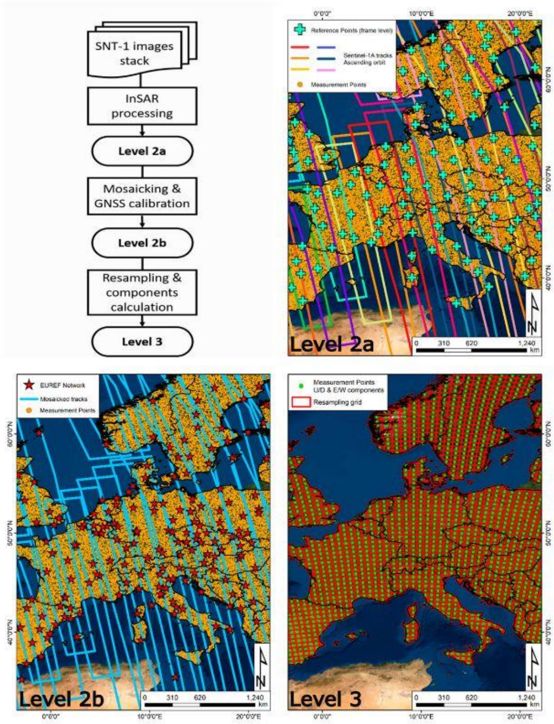

Figure 4 Simplified flowchart of the EGMS product levels (Crosetto et al. 2020)

Each product level holds specific standard feature classes representing a basic set of attributes from meta data and measurement points. These are the LOS "mean-velocity" and "time-series" classes for the Level2a/b products, and the mean-velocity for the vertical and east-west component of the deformation. The quality of the results depends essentially on the data basis, i.e. the type and number of images used. In all services and use cases, the minimum number of images required had been ensured and was significantly exceeded. In contrast to the C-band used on Sentinel-1, X-band sensors (see Table 1 and Table 2) enable higher resolution acquisition and a higher measurement point density (see Figure 5). Accordingly, X-band sensors are suitable constellations for zooming into local phenomena.

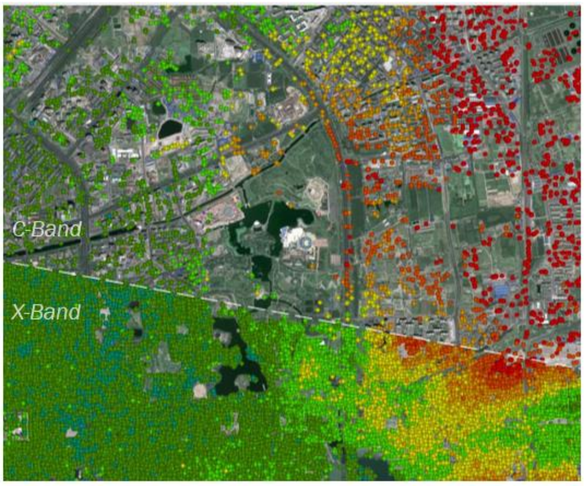

Figure 5 Scalable measurement points in relation to sensor system demonstrated on the example of Beijing. Lower density of measurement points collected by C-band, higher density received by X-band sensor (red measurement points mean negative movements)

2.5 Examples of deformation information measured with PSI

In this chapter, a selection of representative examples using C-band and X-band based PSI are shown, with these being conducted as part of operational services and projects.

Wide area subsidence of opencast-mining (Germany)

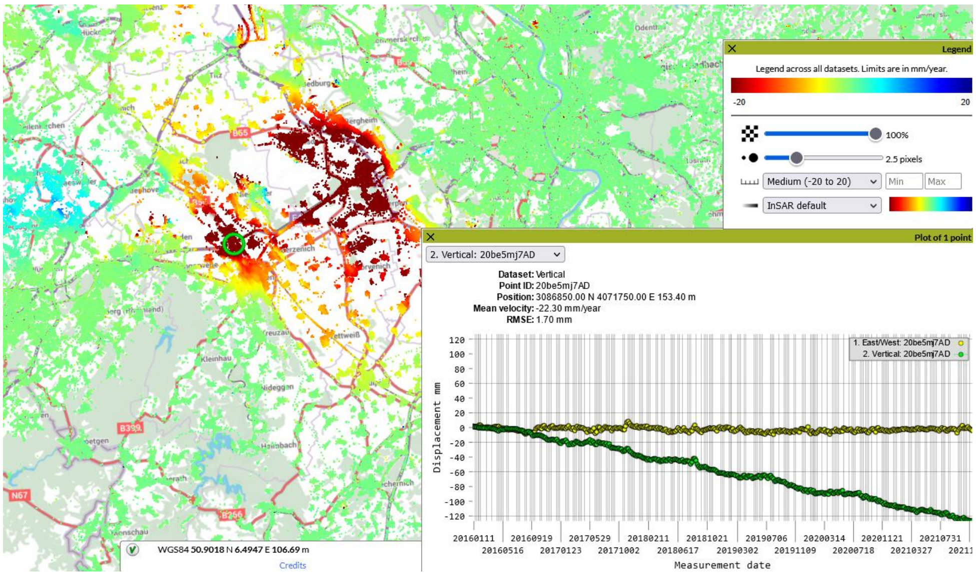

Figure 6 SAR mission/sensor: Sentinel-1 A/1 B; Input data time-series: 2016 – 2021; Vertical ( ) East/West ( ) ground motion over time for opencast mining (subframe) (extracted from https://egms.land.copernicus.eu/ produced with funding from the European Union)

Interpretation: Figure 6 is an extract from Ortho-Product (Level 3) from the EGMS browser (https://egms.land.copernicus.eu/). It visualises the large subsidence area of the opencast mining in Hambach in Germany, which is subject to long-term and permanent groundwater drawdown leading to a significant subsidence rate, while there is no significant mean velocity measured in the East/West direction.

Geothermal drilling (Germany)

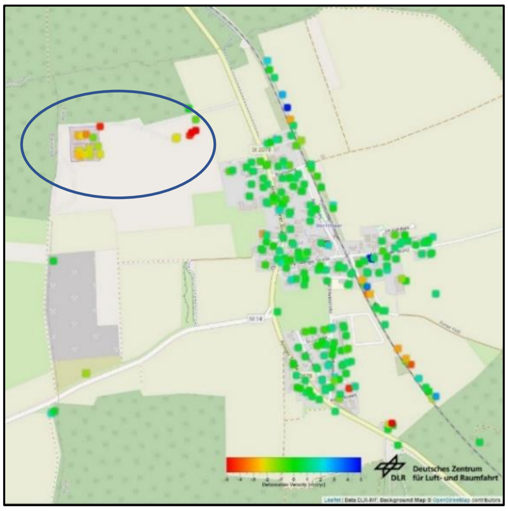

Figure 7 SAR mission/sensor: TerraSAR-X StripMap (3 m), ascending; Input data time-series: 2015 - 2021; PSI LOS measurement points showing negative deformation near a geothermal plant (within the blue ellipse)

Interpretation: Figure 7 represents a zoomed-in example based on TerraSAR-X data. The scope of the project was to monitor the area around geothermal drilling sites regarding the impact of potential seismicity triggered by the drilling. The tendency towards negative values is clearly distinguishable from the measurement points captured from the nearby settlement.

But geothermal drilling does not automatically result in a sagging effect in the ground. Figure 8 shows an example in which geothermal exploitation can also give rise to unexpected swelling of the underground, thereby causing severe damage to buildings and infrastructure. This phenomenon has been experienced for many years, when groundwater penetrates into an anhydrite layer that turns into a more voluminous gypsum.

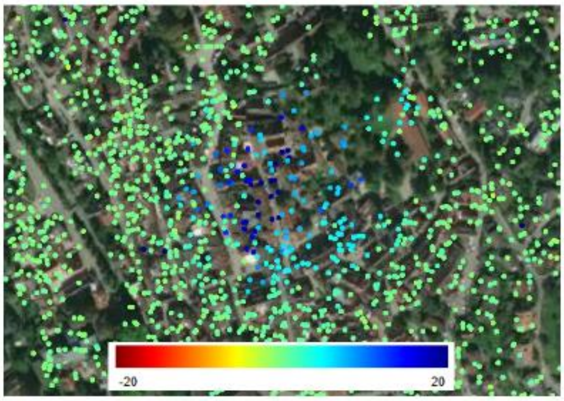

Figure 8 Uplift processes due to geothermal drilling (Germany) – LOS measurement points (https://land.copernicus.eu/user-corner/technical-library/egms-product-user-manual)

Critical infrastructure deformation

The alluvial plain of the Scheldt estuary in the border region of Belgium and the Netherlands is sinking due to human activities, and becoming more vulnerable to flooding. Most of the river basin area is urbanised (average density of ca. 477 inhabitants per km2). The port of Antwerp plays a significant role in terms of the intensive urbanised development of Antwerp and there are 1.2 million inhabitants in the metropolitan area. This area is almost all flat, low-lying, and easily flooded by high tides due to a lack of dikes. The use of InSAR information is illustrated using two examples of EGMS products along the estuary (Declercq et al. 2021): Doel nuclear power plant and the Port of Antwerp. The Doel nuclear power plant is directly located at the coast of the Scheldt estuary.

Figure 9 Overlay of EGMS Level 3 Ortho product covering the Doel nuclear power plant (extracted from https://egms.land.copernicus.eu/ produced with funding by the European Union)

Visualising the vertical motion in the plant area in the EGMS Ortho product shows that subsidence effects in the norther section are related to consolidation processes. Going up to a higher level of detail - the Calibrated products reveal the distribution of measurement points over the physical structure of the power plant area and the related LOS motion (Figure 10).

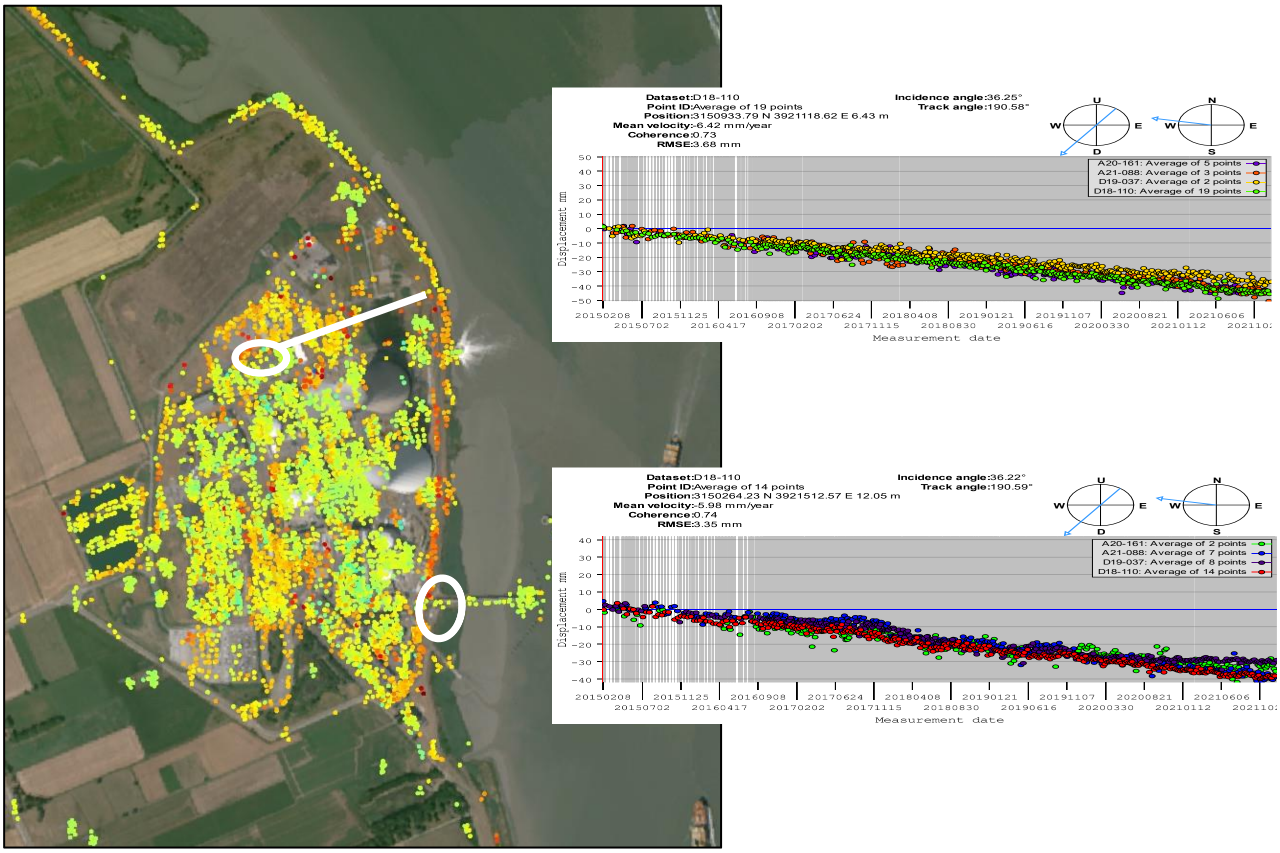

Figure 10 Overlay of EMGS Calibrated product Level 2b covering Doel nuclear power plant (extracted from https://egms.land.copernicus.eu/ produced with funding by the European Union)

For both subsiding clusters shown in the image, approx. -6 mm/year (away from LOS) is detectable – illustrating the previously mentioned consolidation trends.

Port of Antwerp - an example of PS-InSAR measurements in highly industrialised and urbanised areas. This region is of special importance as an economic engine surrounded by the urbanised metropolitan area of Antwerp. Geological studies utilising PS-Analysis were performed along the Scheldt valley and the city of Antwerp, and show that:

- The Antwerp harbour area and the Scheldt valley are mainly characterised by negative annual LOS velocity values during the last 27 years (1992–2019).
- The extensions and developments of the harbour facilities on the alluvial plain of the Scheldt River are based on landfills (distributed across the entire area) affected by land subsidence
- The city centre of Antwerp is stable (near zero annual LOS velocity value); mainly due to the presence of thick sand deposits underneath the urbanised area, which are less sensitive to settlement (sand less compressible) and their age (the deposits are older and thus more consolidated)

These findings are in line with EGMS products, which show the same characteristics (spatial dependencies and deformation patterns)

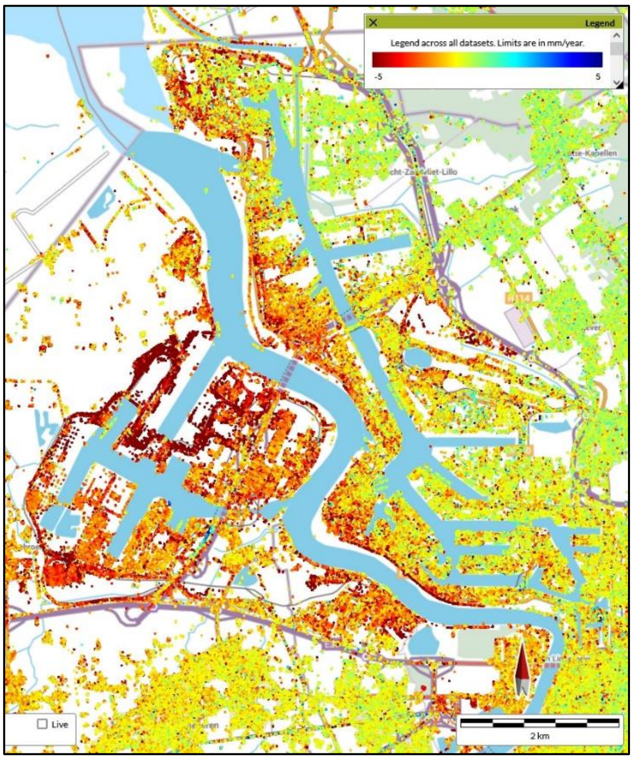

Figure 11 Large and high subsidence of the Antwerp harbour area

EGMS products indicate that:
- Recently established structures in the harbour area show vertical deformation of approx. -15 mm/year
- Quay features along the river move at a sink rate of approx. -10 mm/year
- The historic city of Antwerp is stable at approx. 0 mm/year

2.6 Integration of ground movement information into geo-risk assessments

The identification of low-rate deformation both in the context of natural and man-made hazards, or of man-made structures, respectively, is an essential input parameter within the process of risk assessment. Regular observations provide big measurement point databases for analysis of the localisation, magnitude, frequency, periodicity and seasonality of ground deformation. In combination with ancillary data, e.g. proper elevation data, geological and soil maps, and geohazard activity maps, dedicated high-risk zones can be identified, delineated, classified and aggregated into Active Deformation Areas (ADA) (Figure 13).

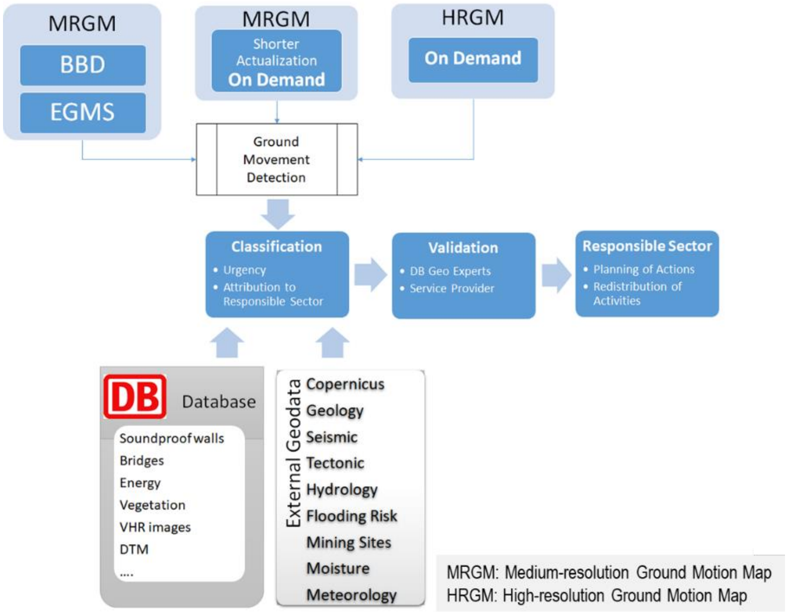

Figure 12 Potential operational workflow for railway monitoring (EO4Infrastructure funded by ESA under the EO-Science for Society)

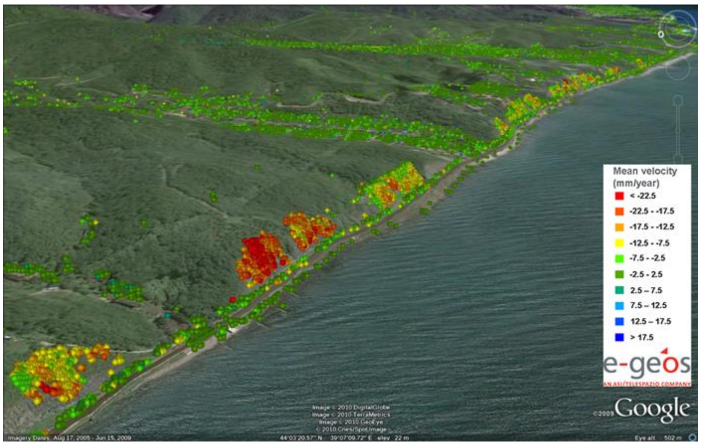

Figure 13 Overlay of measurement points and 3D-visualisation

ADA is reprocessed PSI information made understandable for experts that are not familiar with the interpretation of PSI measurement points. Subsequently, the user can integrate this information into elevation derived information layers like slope, aspect, and drainage, and reassess and enhance existing risk information (Solari et. al. 2017). Barra et al. (2017) presented a methodology in order to generate Deformation Activity Maps (DAM) and Active Deformation Areas (ADA) for easy-to-use subsequent processing in risk management workflows. Navarro et al. (2022) introduced a low-cost concept to generate and publish Activation Deformation Areas for Europe exploiting the information provided by the EGMS. Mele et al. (2023) follows the same concept and elaborates it, focusing on the monitoring of the structural health of urban settlements. Active Deformation Areas are identified and aggregated according to

- temporal coherence
- point density
- acceleration of displacement

followed by a classification that takes into account relevant measurements and thematical features (Figure 14), e.g.

- horizontal and vertical displacement
- geology – tectonics - seismic
- terrain based information extracted from DEM, e.g. slope, aspect, sink drainage
- hydrology
- infrastructure elements

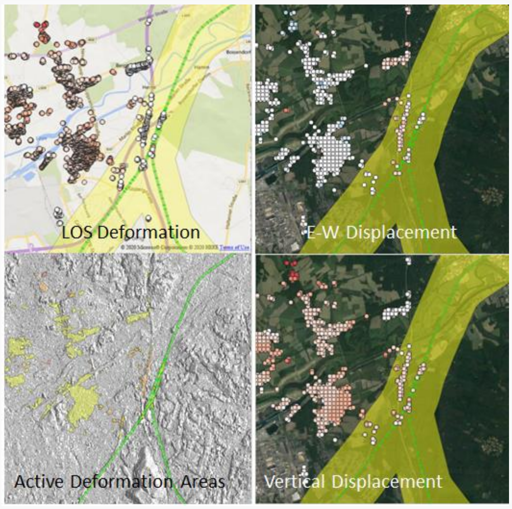

Figure 14 Active Deformation Areas as value-added information

Figure 15 Mean velocity clusters for aggregation into ADA (see also Figure 16)

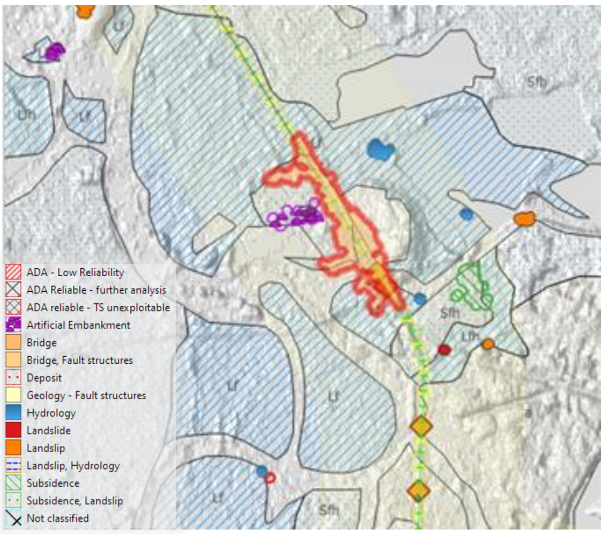

Figure 16 Derived Active Deformation Areas (see also Figure 15)

2.7 Considerations

As one of several InSAR change detection technologies, PSI focuses on the long-term observation approach. The implementation of operational PS-InSAR projects and services at both the international and national levels has proven that PSI time-series analysis is a powerful technique. It is a robust and time-saving method for identifying and monitoring trends in low-rate deformation processes and the effects of counter measurements, and helps prevent and mitigate potential risks that could result from the continuation of ground movements dynamics. The results achieved both globally and locally are impressive, and are recognised in scientific and research communities. However, the PSI technique has certain constraints that can restrict the validity and scope of the information. Additionally, the PSI technique requires a certain amount of expert know-how with regard to the remote sensing SAR technology, and in particular with regard to the immense content of information and its analysis, proper interpretation and valorisation. Accordingly, a lot of effort has to be put into transferring the very specific level of technical detail into easy to ingest and understand applicable information. Moreover, the cost factor is a crucial and critical point to take into account, since in the case of procuring commercial data the images are subject to the specific terms of end-user licence agreements. A recommended starting point here is the vast repository of Sentinel-1 data that has been acquired since the launch of Sentinel-1 A almost 10 years ago as a baseline, and to have a closer look on specific phenomena using very-high-resolution SAR constellations.

3. CONCLUSION AND OUTLOOK

In recent decades, a lot of effort has been put into developing and leveraging the powerful PSI processing technique (Crosetto et al. 2016). At the same time, the availability of free, long-term high-resolution SAR data time series that are unprecedented in terms of consistency, robustness, quality and data access have facilitated and leveraged the intensive and extensive research and development of algorithms, methodologies and technologies within many application fields. The capabilities of EO Big Data have been recognised and accepted as a useful source of bringing benefits in, for example, the disaster risk and response domain. PS InSAR based identification of hidden risks like gradual subsidence endangering constantly growing mega cities can contribute substantially to the prevention and reduction of existing natural or man-made hazards. PS InSAR is a reliable technique for detecting and measuring low-rate ground movements and supplies promising results once long-term data time-series have become available. To ensure the free and open-source policy of the Copernicus Programme, the continuity of the Sentinel-1 mission will be ensured by the launch of the successors Sentinel-1C and 1D. Also, a new generation of Sentinel-1 satellites is being planned, to continue the heritage of the first generation. Accordingly, continuity of data availability is guaranteed. For the commercial sector, many start-ups have discovered and entered the EO market for SAR applications in the past years. Innovation-oriented companies like ICEYE, Umbra SAR, Capella Space, and Synspective generate additional capacities and capabilities focusing on VHR and SuperVHR SAR systems and constellations, thus increasing sampling rates and high-performance data transfer. As a global satellite data broker GAF, AG is engaged in evaluating and benchmarking new satellite sensors in terms of their InSAR capabilities and performances. InSAR core services such as the EGMS or BBD to which GAF AG contributes substantially, serve as a fundamental information source, and an excellent baseline for the generation and supply of global wide or local area processing on request for tailored products. Core products are adapted in line with client and in-situ data, in strong cooperation with local expertise and know-how. Figure 17 gives a general perspective of how Earth observation is expected to develop and trend. Considering the boost to the SAR EO market in terms of the provision of larger and more frequent volumes from new and higher repetitive SAR constellations, there are greater demands regarding efficient Big Data analytic capacities, with the goal of automatically creating customised downstream information products and services, and addressing and satisfying the increasing demand for value-added geoinformation products, in particular in disaster management communities.

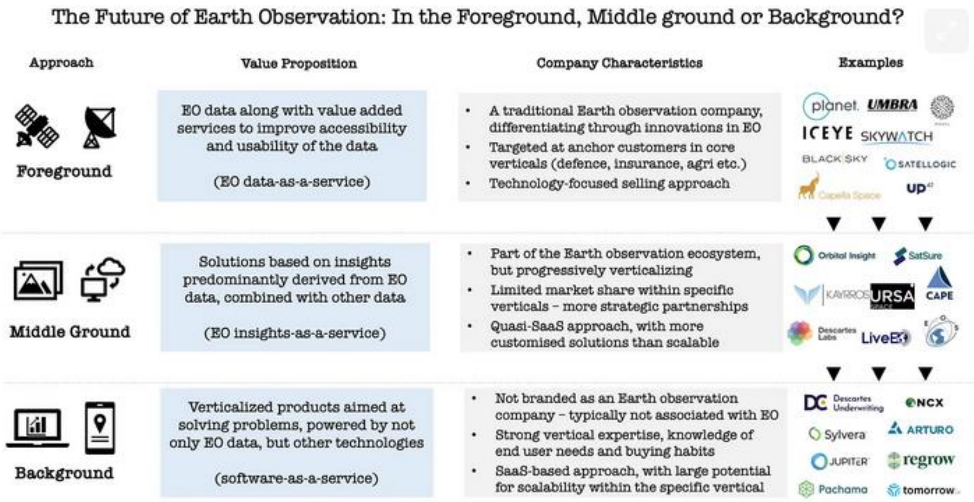

Figure 17 General outlook into future of Earth Observation (Aravind, TerraWatch Space, https://terrawatch.substack.com)

4. REFERENCES

Barra, A., Solari, L., Béjar-Pizarro, M., Monserrat, O., Bianchini, S., Herrera, G., Crosetto, M., Sarro, R., González-Alonso, El., Mateos, r.M., Ligerzana, S., López, C. and Moretti, S., 2017, A Methodology to Detect and Update Active Deformation Areas Based on Sentinel-1 SAR Images, *Remote Sens.* **2017**, *9*(10), 1002; https://doi.org/10.3390/rs9101002

BSI - Federal Office for Information Security, 2023. Retrieved August 2023, from https://www.bsi.bund.de/EN/Themen/KRITIS-und-regulierte-Unternehmen/Kritische-Infrastrukturen/Allgemeine-Infos-zu-KRITIS/allgemeine-infos-zu-kritis.html

Cao, A., Esteban, M., Valenzuela, V.P.B., Onuki, M., Takagi, H., Thao, N.D. and Tsuchiya, N., 2021, Future of Asian Deltaic megacities under sea level rise and land subsidence: current adaptation pathways for Tokyo, Jakarta, Manila, and H Chi Minh City, Current Opinion in Environmental Sustainability 2021, 50:87-97, Science Direct, https://www.sciencedirect.com/science/article/pii/S1877343521000361?via%3Dihub

CISA - Cybersecurity & Infrastructure Security Agency, 2023, Retrieved August 2023, from https://www.cisa.gov/topics/critical-infrastructure-security-and-resilience/critical-infrastructure-sectors

Crosetto, M., Solari, l.; Mróz, M., Balasis-Levnisen, J., Casagli, N., Fri, M., Qyen, A., Moldestad, D.a., Bateson, L., Guerrieri, L., Comerci, v., Andersen, H.S., 2020, The Evolution of wide-Area DInSAR: From Regional and National Services to the European Ground Motion Service, Remote Sensing, 2020, 12(12), 2043; https://doi.org/10.3390/rs12122043

Crosetto, M., Monserrat, O., Cuevas-González, M., Devantheréry, N., Crippa, B., 2016, Persistent Scatterer Interferometry: A review, ISPRS Journal of Photogrammetry and Remote Sensing 115 (2016) 78 - 89

Declercq, P.-Y.; Gérard, P.; Pirard, E.; Walstra, J.; Devleeschouwer, X., 2021, Long-Term Subsidence Monitoring of the Alluvial Plain of the Scheldt River in Antwerp (Belgium) Using Radar Interferometry. Remote Sens. 2021, 13, 1160. https://doi.org/10.3390/rs 13061160

Erkens, G., Bucx, T., Dam, R., Lange de, G., and Lambert, J., 2015. Sinking coastal cities. Proc. IAHS, 372, 189–198, 2015, doi:10.5194/piahs-372-189-2015, https://www.researchgate.net/figure/Land-subsidence-and-groundwater-levels-in-the-Tokyo-area-Japan-modified-after-Kaneko_fig7_283771445

European Environmental Agency (EEA), 2023a, End-to-end implementation and operation of the European Ground Motion Service (EGMS) Algorithm Theoretical Basis Document, Version 2.0, https://land.copernicus.eu/user-corner/technical-library/egms-algorithm-theoretical-basis-document

European Environmental Agency (EEA), 2023b, End-to-end implementation and operation of the European Ground Motion Service (EGMS), Quality Assurance & Control Report: First update, https://land.copernicus.eu/user-corner/technical-library/egms-quality-assurance-control-report

European Environmental Agency (EEA), 2022, End-to-end implementation and operation of the European Ground Motion Service (EGMS), Product User Manual, Version 1.6, https://land.copernicus.eu/user-corner/technical-library/egms-product-user-manual

European Environmental Agency (EEA), 2021, End-to-end implementation and operation of the European Ground Motion Service (EGMS), End User Requirements, Version 1.0, https://land.copernicus.eu/user-corner/technical-library/egms-end-user-requirements-document

European Commission, 2023, Climate Bulletins, https://climate.copernicus.eu/climate-bulletins

Fischer, L., 2022. Welche Städte am schnellsten versinken. Spektrum.de, https://www.spektrum.de/news/welche-staedte-am-schnellsten-absinken/2056935

Hengxing, I., Langping, L., Hongjiang, L., Zhihua, Y., 2012, Complex Urban Infrastructure Deformation Monitoring Using High Resolution PSI, IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing · April 2012

IPCC, Climate Change 2023, AR6 Synthesis Report, https://www.ipcc.ch/report/ar6/syr/

Kandarr, J., 2018. Coastal cities are sinking dramatically. ESKP, https://www.eskp.de/en/natural-hazards/coastal-cities-are-sinking-dramatically-935926/

Kawade, P., 2022, Earth Observation Growth Engine: SAR, https://www.nsr.com/earth-observation-growth-engine-sar/

Navarro, J. A., García, D., Crosetto, M., Monserrat, O., 2022, Processing and Publishing the Active Deformation Areas of all Europe – Concept and First Implementation Steps for a Low-cost Solution, The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLIII-B3-2022, XXIV ISPRS Congress (2022 edition), https://isprs-archives.copernicus.org/articles/XLIII-B3-2022/313/2022/isprs-archives-XLIII-B3-2022-313-2022.pdf

Navarro, J. A., Tomaás, R., Barra, A. and Pagán, J. I., 2020, ADAtools: Automatic Detection and Classification of Active Deformation Areas from PSI Displacement Maps, ISPRS International Journal of Geo-Information 9(9):584

Navarro, j. A., Cuevas, M., Tomás, R., Barra, A. and Crosetto, M., 2019, A Toolset to Detect and Classify Active Deformation Areas using Interferometric SAR Data, Proceedings of the 5th International Conference on Geographical Information Systems Theory, Applications and Management (GISTAM 2019), pages 167-174

Mele, A., Crosetto, M., Miano, A. and Prota, A., 2023, ADAfinder Tool Applied to EGMS Data for the Structural Health Monitoring of Urban Settlements, *Remote Sens.* **2023**, *15*(2), 324; https://doi.org/10.3390/rs15020324

Rodriguez, F.G., Adam, N. A., Parizzi, A., Brcic, R., 2013, The Integrated Wide Area Processor (IWAP): A Processor For Wide Area Persistent Scatterer Interferometry, Proceedings of ESA Living Planet Symposium 2013, https://livingplanet2013.org/abstracts/850572.htm

Solari, L., Barra, A., Herrera, G., Bianchini, S., Monserrat, O., Béjar-Pizarro, M., Crosetto, M., Sarro, R. and Moretti, S., 2017, Fast detection of ground motions on vulnerable elements using Sentinel-1 InSAR data, Geomatics, Natural Hazards and Risk, Pages 152 – 174,

Tapete, D., Cigna, F., 2017, InSAR data for geohazard assessment in UNESCO World Heritage sites: state-of-art and perspectives in the Copernicus area, International Journal of Applied Earth Observation and Geoinformation, Vol. 63, December 2017, Pages 24 -32

Universität Stuttgart – Fakultät 6: Luft- und Raumfahrttechnik und Geodäsie, accessed in August 2023, https://www.f06.uni-stuttgart.de/studium/studium_gug/allgemein/fernerkundung/

Wu, P.-C., Wie, M. and D´Hondt, S., 2022. Subsidence in Coastal Cities Throughout the World Observed by InSAR. AGU, Geophysical research Letters, https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2022GL098477

Xiao, R., Chen, Y., Zhenhong, L., Jiang, M. He, X., InSAR stacking with atmospheric correction for rapid geohazard detection: Applications to ground subsidence and landslides in China, International Journal of Applied Earth Observation and Geoinformation, Volume 115, December 2022, 103082